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ORIGINAL PAPER - EXPLORATION GEOLOGY

Reservoir characterization and origin of tight gas sandstones in the Upper Triassic Xujiahe formation, Western Sichuan Basin, China

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Abstract The Western Sichuan Basin, which is located at the front of Longmen Mountain in the western Sichuan Province, China, is a foreland basin formed in the Late Triassic. The Upper Triassic Xujiahe formation in the Basin includes several tight gas sandstone reservoirs, whose porosity is less than 6.0 % and permeability less than 0.1 md. According to data of cores, thin sections, FMI, SEM and experiments, we summarize the reservoir characteristics, analyze the origin of these tight gas sandstones, and discuss the factors controlling the formation of relatively high-quality reservoirs. Xujiahe Formation is a set of terrestrial clastic rocks with low compositional maturity, low cement content, and medium textural maturity. Secondary dissolution pores are abundant, but pore spaces are small with narrow pore throats and high capillary pressures. Due to the existence of abundant fractures and intense diagenesis, these tight gas reservoirs are characterized by high reservoir heterogeneity, complex seepage system, and strong stress sensitivity. The original sedimentary facies belt and later tectonism co-control the distribution of favorable reservoirs. The intense compaction and cementation are the main factors making the Xujiahe formation to be tight.

Keywords Tight gas sandstones · Reservoir characteristics · Origin · High-quality reservoirs · Controlling factors

Introduction

Tight gas reservoirs are referred to gas-bearing rocks with in situ permeability to gas of less than 0.1 md (Zhu et al. 2008; Zou 2011; Ameen et al. 2012). With demand for oil and gas resources increasing, attention is sharply focused on unconventional resources. Much of this attention is directed at tight gas sandstones (Shanley et al. 2004; Zhu et al. 2008; Zou 2011). The Upper Triassic Xujiahe Formation in the Western Sichuan Foreland Basin develops abundant gas sources with thick reservoirs, large traps, and good sealing conditions. It is equipped with the gas accumulation conditions for forming large gas field, and has huge exploration potential (Wei et al. 2005; Zhu et al. 2009). But the Western Sichuan Foreland Basin experienced complicated tectonic evolution and intense diagenesis. Most of the reservoirs are tight gas sandstones with low porosity, ultralow permeability, well-developed fractures, and great reservoir heterogeneity. All of these made it difficult to identify sand bodies and reservoirs (Qin et al. 2007; Tian et al. 2008). According to data of cores, thin sections, and experiments, this paper discusses the geological characteristics and origin of tight gas sandstone reservoirs and the factors controlling the formation of relatively high-quality reservoirs.

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Geological setting

Structure

The Western Sichuan Foreland Basin is located on the eastern side of Longmen Mountain thrust belt, south of the Micang Mountain, west of the middle Sichuan uplift, and north of the Emei-Washan faulted and folded zone (Fig. 1). It is a NE–SW oriented elongated belt with an area of 31,000 km^2. This foreland basin formed during the Late Triassic (Burchfiel et al. 1995; Chen and Wilson 1996; Jin et al. 2010). Two main groups of NE–SW and N–S thrusts and their associated fold structures exist. The faults have high throw and have trace lengths of tens of kilometers. Most faults cut the Upper Triassic to the Upper Jurassic strata, but several cut Cenozoic strata (Robert et al. 2010; Zeng and Li 2010; Zeng 2010).

Stratigraphy

Before the Middle Triassic, the Western Sichuan Foreland Basin was dominated by shallow marine carbonate deposition. From the Late Triassic, the basin was filled with continental detrital deposits with a gross thickness of more than 10,000 m. Of these deposits, the Upper Triassic Xujiahe formation is the primary gas-bearing unit and the primary exploration target. The Upper Triassic Xujiahe Formation is sandstone mixed with mudstone and coal streaks, which is overlying on the Middle Triassic Leikoupo formation unconformably and overlaid by the Lower Jurassic Zhenzhuchong formation (Fig. 2). Xujiahe Formation can be divided into five Members from bottom to top (Xie et al. 2008; Zhu et al. 2009; Zou et al. 2009). The first Member is chiefly dark gray to black shale, the second Member is chiefly grayish white to light gray fine- to medium-grained sandstone, the third Member is dark gray to black shale with light gray fine-grained sandstone, the fourth Member is dark gray rock-fragment sandstone with thin shale, and the fifth Member is gray to black shale and argillaceous siltstone. Among them, the second and the fourth Member are the main reservoirs in the study area, which is also the focus of our study. And the first, the third, and the fifth Member play a role of source rock (Fig. 2).

Exploration and development history

The western Sichuan Foreland Basin was the first natural gas exploiting area in china. According to historical records, several shallow wells drilled at the study area produced small quantities of natural gas for boiling salt and lighting 1800 years ago (Zhai, 1989). The large-scale exploration works were launched in the 1950s. The study of Xujiahe Formation began in the 1970s. The first commercial natural-gas-producing well (Zhong4 well) of Xujiahe Formation in Zhongba Structure began production

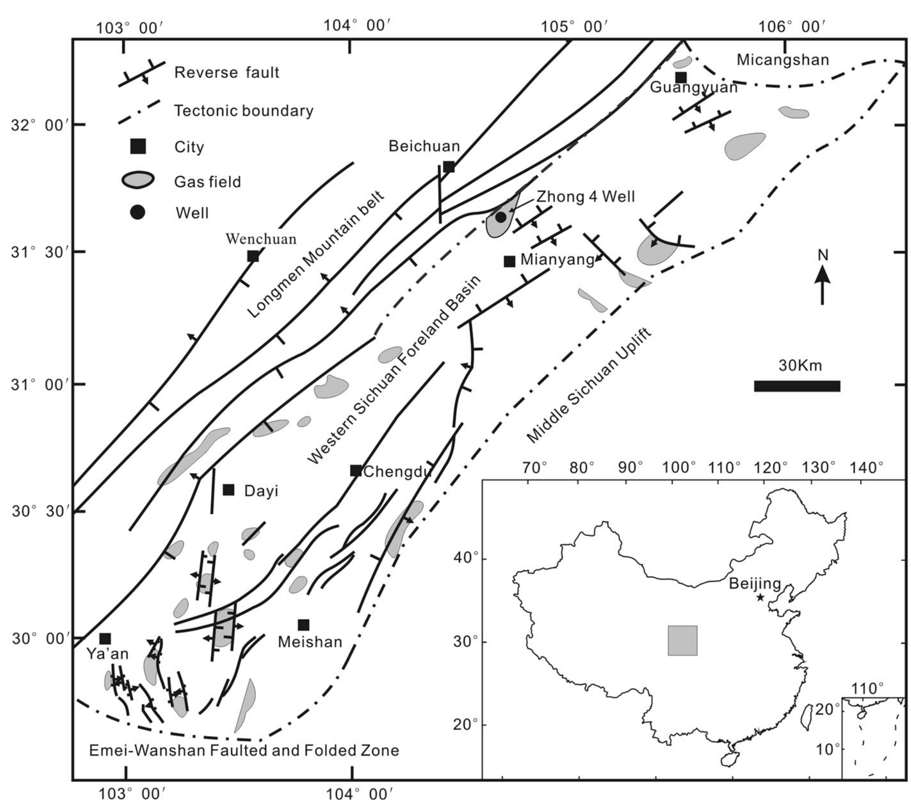

Fig. 1 Map showing location of the Western Sichuan Foreland Basin

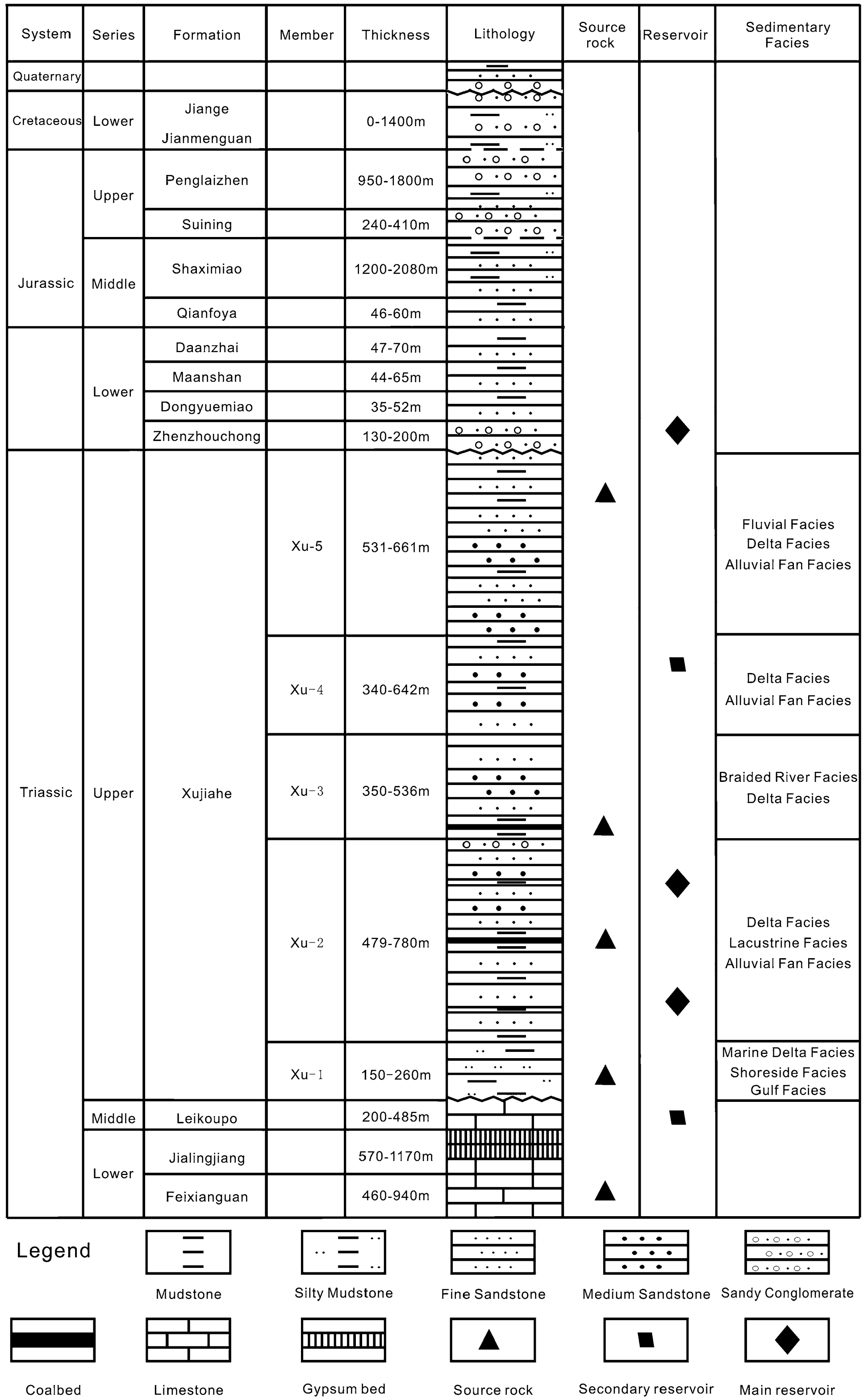

Fig. 2 Schematic stratigraphy, source rock, and reservoir in the Western Sichuan Foreland Basin

in the 1970s (Fig. 1). Since then, more than 300 exploration and production wells have been drilled, and more than 20 gas fields have been discovered and produced (Fig. 1). After 2000, it turned into a new stage of accelerating the exploration and development of Xujiahe Formation. Many studies demonstrated that the Xujiahe

Formation was equipped with good combination of source rock, reservoir, and cap rock, which is favorable for forming medium or large-size gas fields (Xie et al. 2008; Zhu et al. 2009; Zou et al. 2009; Zeng and Li 2010). But it also had exploration difficulties and risks because of the complicated geological conditions. Consequently, it has a very important significance for finding exploration targets to study the geological characteristics of tight gas sandstones of Xujiahe Formation.

Datasets and methods

All samples are collected from the bore holes, including Zhong 4 and other 21 wells. Among these, most samples are from the second and fourth Member of the Xujiahe Formation. Petrographic observations are used to identify clastic composition, paragenetic sequence of authigenic minerals, and characters of pore textures. Petrographic observation is aided by SEM (scanning electron microscope), cathode luminescence, X-diffraction, carbon and oxygen isotope of carbonate cements to define the diagenetic evolution (Zhu et al. 2009). After that, representative samples were selected to measure homogenization temperatures of inclusions and analyze their compositions.

Reservoir characteristics

Sedimentary environment and lithological characteristics

Except for the locally developed paralic facies deposition in the first Member, all the other intervals in Xujiahe Formation are terrestrial deposition (Zhang et al. 2009; Zhu et al. 2009; Zhao et al. 2011). From the basin margin to the subsidence-depositional center of the basin, the sedimentary facies has the distribution characteristics of successively alluvial fan facies, fan delta facies, fluvial facies, fluvial delta facies, and lacustrine facies (Fig. 3).

The reservoir lithology is mainly fine- to medium-grained feldspathic litharenite and lithic sandstone, and secondarily lithic quartzose sandstone and feldspathic quartzose sandstone. Grains are well to medium sorted, with sub-rounded shapes. Tight gas sandstones of Xujiahe Formation have low compositional maturity, low cement content, and medium textural maturity. Quartz contents usually are 24.0–70.0 % with maxima of 86.0 %. Lithic fragments usually are 12.0–35.0 % with an average of 16.6 %. Feldspar contents usually are 2.0–18.0 %. And the contents of cements are 4.0–6.0 %. The cements are mainly composed of silicious cement, chlorite, calcite, and dolomite.

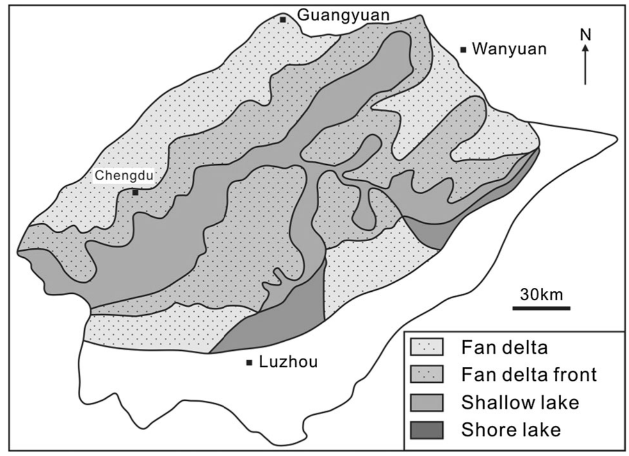

Fig. 3 Sedimentary facies distribution of the second Member in Xujiahe Formation, Sichuan Basin

Pore structure of reservoirs

According to analysis of casting thin sections and scanning electron microscope images, secondary pores (account for 85 %) and micro-fractures (account for 8 %) are the main pore types (Fig. 4), while primary pores (account for 7 %) are rare. Secondary pores are intragranular and intergranular dissolution pores created by the dissolution of feldspars and lithic fragment. Feldspar is often dissolved along the cleavage and micro-fracture, and thus forms cancellate intragranular dissolved pore. Some even form moldic pore, which was almost dissolved completely. Feldspar dissolved pore is the major storage space of Xujiahe Formation reservoir in the study area. The cast thin section statistic data show that the porosity in Xujiahe Formation result from dissolution is generally lower than 3.0 %. The average is 2.0 % and the highest value can reach 5.0 %. On the whole, the feldspar content of Xu-2 Member is higher than that of Xu-4 Member. The secondary dissolved pore is relatively well developed, and the statisticed thin section area-pore-ratio can reach 3.2 %. Primary pores include residual intergranular pores and micro-pores in the matrix. The pore radius is in the range of 12.6–100.0 μm with an average of 25.6 μm. The maximum pore throat diameter is generally about 0.31–5.13 μm with an average of 1.82 μm. The mean pore throat radius is 0.008–0.35 μm, averaging 0.09 μm. The sorting coefficient of pore throat is 2.05–3.97 with an average of 2.73. On the whole, the pore structure of the tight gas sandstones in Xujiahe Formation has characteristic of small pore throat, lacking of effective pore throat and poorly pore throat sorting.

Porosity and permeability

According to the reservoir characteristics analysis of more than 26,000 samples from 18 gas field of Western Sichuan

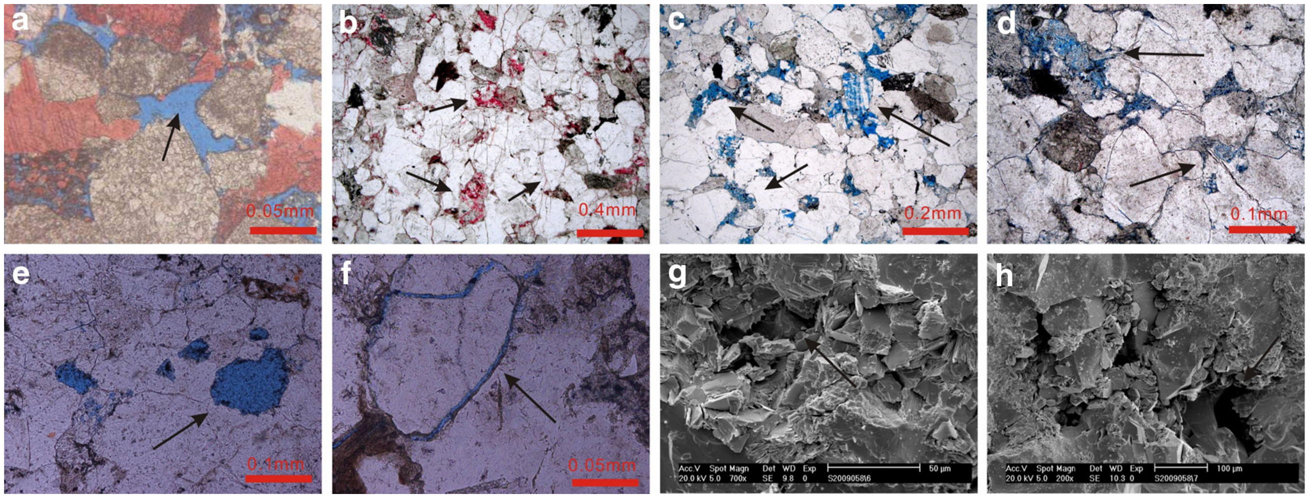

Fig. 4 Pore types **a** Intergranular dissolution pores (*blue dye*), polarizing light, depth 3478.02 m; **b** micro-fractures and intragranular dissolution pores (*red dye*), polarizing light, depth 3455.3 m; **c** intergranular and intragranular dissolution pores (*blue dye*), polarizing light, depth 3476.18 m; **d** intragranular dissolution pores (*blue dye*), polarizing light, depth 3867.34 m; **e** moldic pores (*blue dye*), polarizing light, depth 3880.89 m; **f** grain-edge fractures dissolved from chlorite lining (*blue dye*), polarizing light, depth 3882.34 m; **g** residual intergranular pores, depth 3094.15 m; **h** dissolution pores and residual intergranular pores, depth 3095.56 m

Foreland Basin, the porosity of Xujiahe Formation is less than 6.00 %, and the permeability is less than 0.1 md. The porosity of the second Member is mainly distributed at 2.00–6.00 %, and the average porosity is 3.59 % (Table 1; Fig. 5). The permeability of the second Member is mainly distributed at 0.010–0.100 md, and the average permeability is 0.064 md (Fig. 5). The porosity of the fourth Member is mainly distributed at 1.00–5.00 %, and the average porosity is 2.73 % (Fig. 5). The permeability of the second Member is mainly distributed at 0.005–0.100 md, and the average permeability is 0.038 md (Fig. 5). Generally speaking, the physical property of the second Member is better than the fourth Member.

Fracture distribution

According to the data of outcrops, cores, thin sections, and logging, the fractures in the tight gas sandstones of the Upper Triassic Xujiahe Formation can be divided into 3 types, i.e., tectonic fractures, diagenetic fractures, and fractures related to overpressure (Zeng and Li 2010). Among them, tectonic fractures are the most important.

In terms of dip angles, tectonic fractures can be subdivided into high-angle fracture with a dip angle of more than 70° and approximately horizontal fracture with a dip angle of 10°–30° (Fig. 6). The high-angle fractures mostly are tectonic shear fractures, distributed in all kinds of lithology. These fractures have steady occurrences, flat and smooth fracture surfaces, and show an echelon array (Fig. 6a). There often have striations and steps on the fracture surface. The approximately horizontal fractures are mainly distributed in the medium-grained sandstones and gritstones nearby the thrust belts or sliding layers. They are not entirely parallel but slightly oblique to the micro-bedding plane, and have equal spacing (Fig. 6b). Some of them are filled with calcite, quartz, and bitumen. Some scholars thought that these approximately horizontal fractures were formed due to unloading (Yu et al. 2006). According to the characteristics of such fractures in the study area, we deduce that they are natural tectonic shear fractures formed

Table 1 Statistics of porosity and permeability of tight gas sandstones in the Xujiahe Formation in Western Sichuan Foreland Basin (WSFB)

Member	Region	Mean porosity (%)	Mean permeability (md)	Sample number
The second member	North of the WSFB	3.42	0.053	4986
	South of the WSFB	2.58	0.036	7125
	Middle of the WSFB	4.98	0.097	5828
	Total	3.59	0.064	17,937
The fourth member	North of the WSFB	1.21	0.019	1184
	South of the WSFB	1.63	0.006	2986
	Middle of the WSFB	3.80	0.059	4778
	Total	2.73	0.038	8948

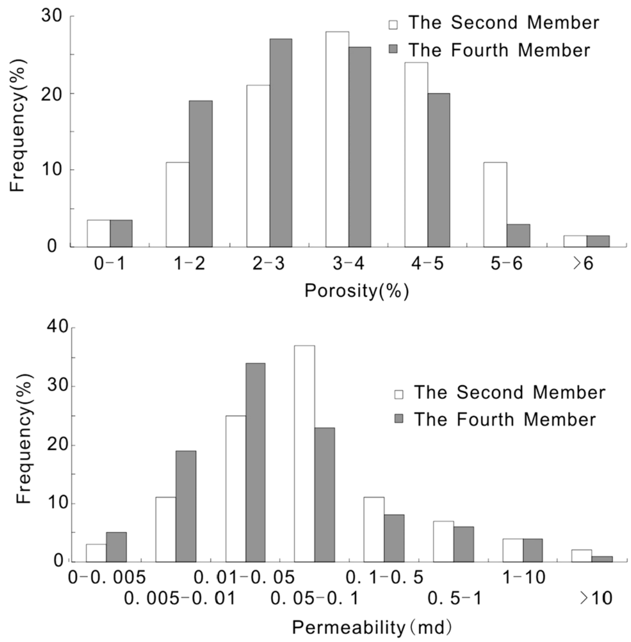

Fig. 5 Distribution of porosity and permeability of tight gas sandstones in the Xujiahe Formation

during multi-period tectonic events and that their origin is mainly related to horizontal shear arising from thrusting or interlayer sliding under tectonic compression. The formation of these approximately horizontal shear fractures in the fold-thrust belts is also validated by numerical simulation (Zeng et al. 2009).

Diagenetic fractures chiefly occur along the bedding in the fine sandstone, and are characterized by bending, discontinuation, branching, and punchout (Fig. 6c). These fractures are sometimes densely spaced, but they are distributed discontinuously and have poor lateral connectivity, and are tiny apertures under lithostatic pressure conditions. Fractures related to overpressure are usually tensional veins filled with bitumen or calcite (Fig. 6d). Their occurrences vary greatly, and have no regularity.

Heterogeneity of reservoirs

Compared with conventional low-permeability sandstone reservoirs with permeabilities being 10–50 md, the tight gas sandstone reservoirs of Xujiahe Formation in the western Sichuan Foreland Basin have a greater heterogeneity, which can be divided into macro- and micro-heterogeneity. The macro-heterogeneity is mainly caused by sedimentation, and contains heterogeneity between layers, in the single layer and in the plane, shown as the varying of petrographic composition, grain size, sorting, sedimentary structure, rhythm, and the diversity of connectivity in the plane. Micro-heterogeneity is mainly caused by diagenesis, and often refers to the variation of pore type, pore throat size, and pore structure. Furthermore, the existence of fractures is a very important factor causing the heterogeneity of permeability in the tight gas sandstones. Because of the difference of development degree, apertures, and connectivity of different oriented fractures under the influence of current- and palaeo-stress field, the permeability of different oriented fractures varies greatly. For example, according to the calculation result by the Monte Carlo method, the permeability of the NW–SE, NE–SW, E–W, and N–S oriented fractures is, respectively, 43.4, 15.0, 11.6, and 10.4 md. The NW–SE oriented fractures which are parallel to the maximum principal stress direction of current stress field have the biggest permeability, and are the dominant seepage channels of the study area.

Seepage features

Because the matrix of tight gas sandstones in Xujiahe Formation is characterized by poor pore structure, small pores, narrow pore throats, and low permeability, the resistance to fluid flow is great, and the interacting forces at the interfaces of solids and liquids are strong. Therefore, a clear start pressure gradient exists and the fluid flow is not coincident with the Darcy law. Start pressure is inversely proportional to matrix permeability (Shanley et al. 2004; Friedel and Voigt 2006). The lower the permeability is, the higher the start pressure is, and the greater the influence on the development. Meanwhile, because of the existence of well-developed fractures, the high fracture conductivity contrasts with the low matrix permeability, making the flow system complex.

Stress sensitivity

According to analysis of stress sensitivity test (Fig. 7), the stress sensitivity of the sandstones is moderate when the samples have no fractures. However, when fractures present, the stress sensitivity is obvious. As the decrease of formation pressure, the permeability decreases rapidly and then decreases less rapidly. Even if the formation pressure subsequently increases, the permeability cannot return to its original value, even the 15 % of the original permeability. So, gas producing rate should be kept in a reasonable speed, or it may generate irreversible permeability harm.

Origin of tight gas sandstones

Compaction and pressure solution

Mechanical compaction is the most important factor that caused the Xujiahe Formation sandstone to be tight. In order to describe the damage degree of pores caused by mechanical compaction and analyze the controlling factors

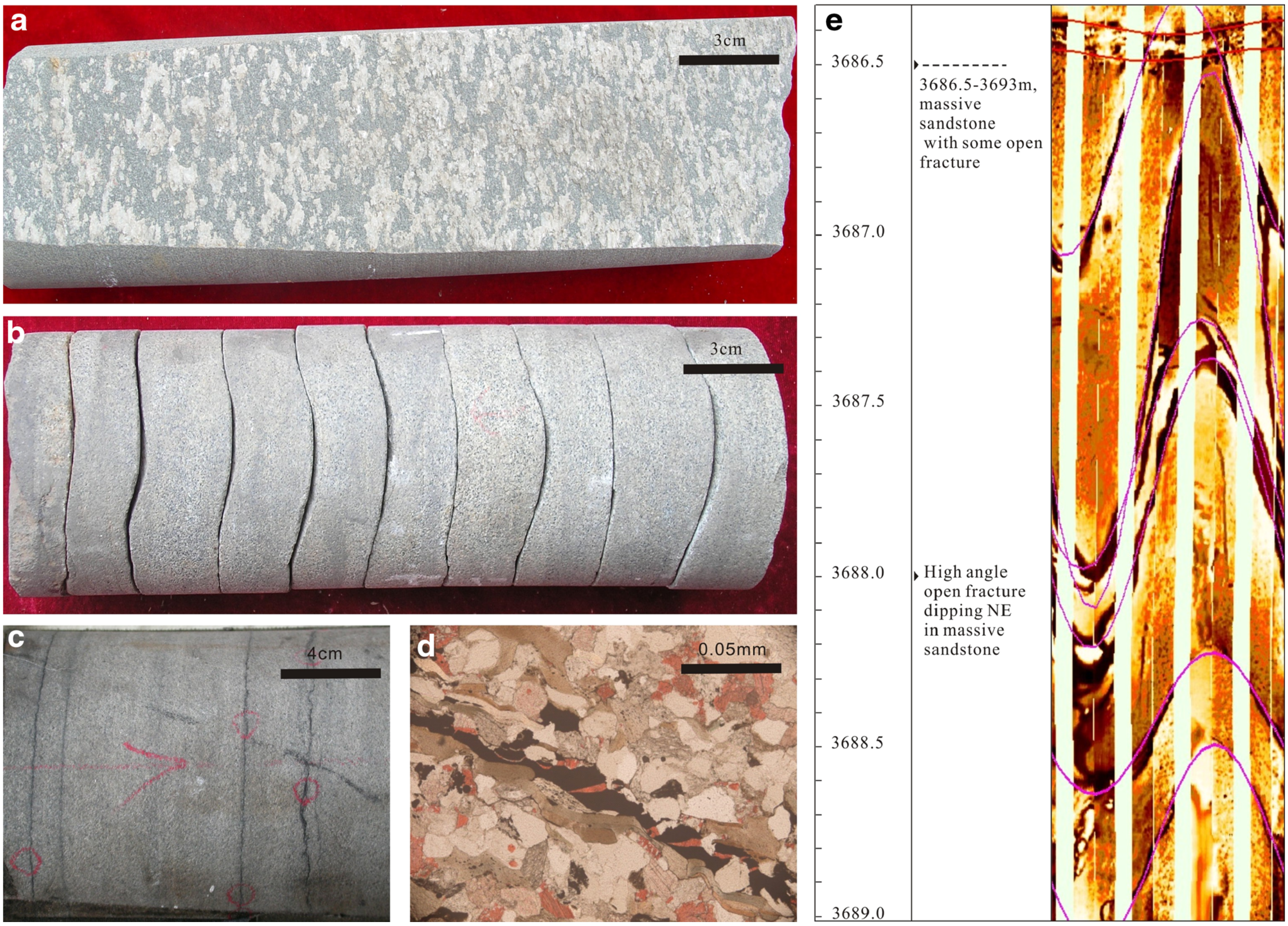

Fig. 6 Fracture types **a** high-angle fracture in core, L9 well, 3458.45 m; **b** approximately horizontal fractures with good equal spacing, L9 well, 3470.42 m; **c** diagenetic fractures parallel to bedding planes, QX1 well, 4234.20 m; **d** fractures related to overpressures, JM3 well, 3495.35 m; **e** high-angle open fracture in FMI, L8 well, 3688 m

causing compaction, we calculate the apparent compaction ratio (ACR). The ACR is defined as

$$\mathrm{ACR} = ((\mathrm{PP} - \mathrm{IP} - \mathrm{C})/(\mathrm{PP})) \times 100,$$

where ACR is the apparent compaction ratio, PP is primary porosity, IP is the content of intergranular pore, and C is the content of cement. According to the statistics of the ACR of more than 8000 samples, the ACR of most samples from the tight gas sandstones of Xujiahe Formation is larger than 70 %, and the absolute loss of porosity caused by compaction is about 30 %. Mechanical compaction is the most important factor that caused the reduction of porosity and reservoirs to be tight. Three factors made the compaction intense. Deep burial depth is the first factor. The maximum historical burial depth of Xujiahe Formation is generally more than 4000 m, and some where can reach 7200 m. The deep burial depth is the main factor causing compaction intense. The burial history is the second factor (Fig. 8). All the formations of Xujiahe Formation in the Western Sichuan Foreland Basin experienced the quick burial in early stage (Yanshan Movement), making the sediments had poor sorting and moderate psephicity and easily to be tight in the influence of great lithostatic pressure. After that, the formation experienced another phase of deep burial in early Himalayan Movement with common depth of 5500–6000 m. The deep burial time is long and the influence is adequate. Thus, the compaction is strong. The difference of grain composition is the third factor. The increase of plastic grains made the compaction intense easily.

With the increase of burial depth and lithostatic pressure, chemical pressure solution occurred along the boundary between grains sutured together by mechanical compaction. Chemical pressure solution further reduced the storage space.

Cementation

Cementation is an important pore destructor. As the increase of temperature and pressure, authigenic mineral formed because of the supersaturation of mineral in the interstitial water. The cements of tight gas sandstones in the Xujiahe Formation are mainly carbonate mineral and quartz, and

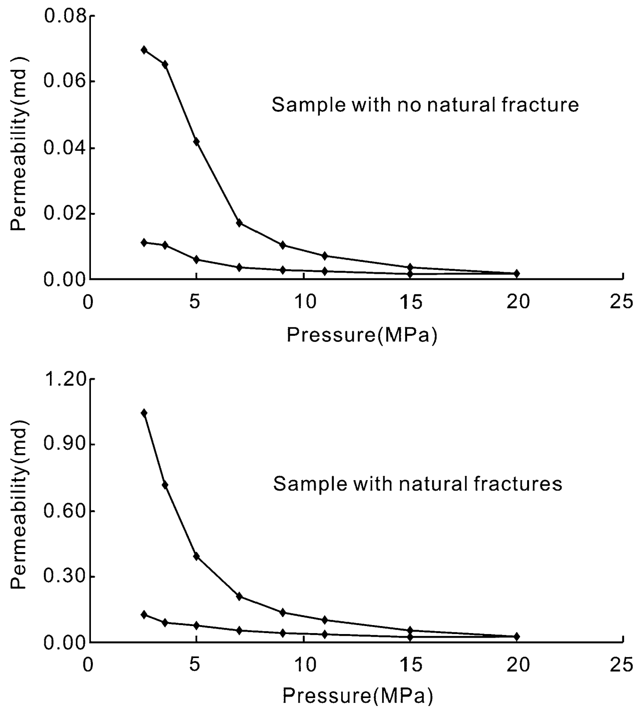

Fig. 7 Pressure sensitivity curve of the permeability of the tight gas sandstones in Xujiahe Formation

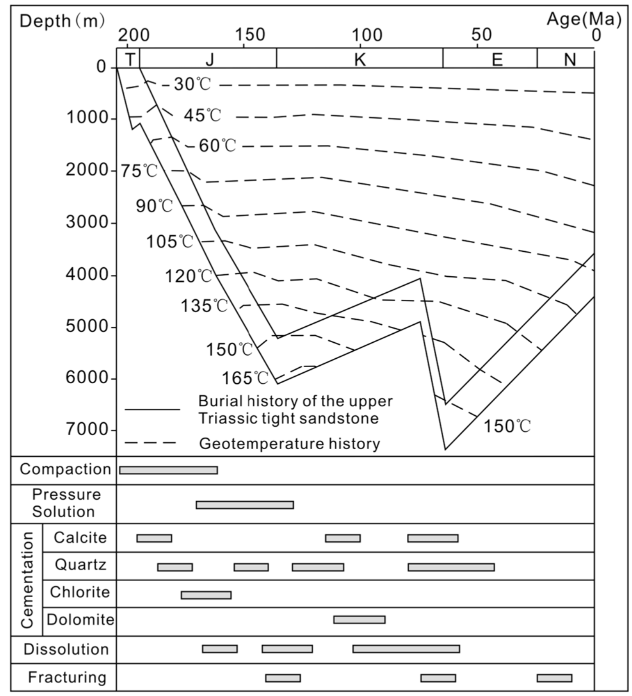

Fig. 8 Burial history and diagenetic sequence of the tight gas sandstones of Xujiahe Formation

secondly chlorite and clay minerals (Xie et al. 2008; Yang et al. 2008; Zhu et al. 2009). According to the paragenetic association relationship between various diagenetic minerals, Zhu et al. (2009) initially determined the relative sequence of diagenetic mineral forming from early to late (Fig. 8): early stage calcite → I phase quartz overgrowth → chlorite film → feldspar and lithic fragment dissolution → chlorite pore lining → II phase quartz overgrowth (overgrowth, residual intergranular pore and intergranular dissolved pore filled with quartz) → denudation → III phase quartz overgrowth (intergranular dissolved pore and intragranular pore filled with quartz) → intergrowth calcite → dolomite → ankerite (calcite) → late denudation → forming of quartz and calcite veins. The carbonate cement and the I phase quartz overgrowth did not develop well, and thus they have small influence on reservoir quality. The reservoir filled with chlorite has relatively better property. The II and III phase quartz overgrowth and cement development are important factors for sandstone tight.

Dissolution

With the increase of burial depth, organic matter decarboxylation occurred, making the interstitial water to be acidic, and then dissolution came up (Zhu et al. 2009). Feldspar and lithic fragment are the main dissolution minerals in the Xujiahe Formation. Feldspar is often dissolved along the cleavages and cracks, and thus producing alveolate intragranular dissolved pores. Some feldspars even were almost dissolved completely forming moldic pores (Fig. 4e). Feldspar dissolved pore is the major storage space of tight gas sandstones of Xujiahe Formation in the Western Sichuan Foreland Basin.

According to statistic data of casting thin sections, the porosity of tight gas sandstones in Xujiahe Formation result from dissolution is generally lower than 3.0 % with an average of 2.0 %, and the highest value can reach 5.0 %. On the whole, the feldspar content of the second Member is higher than the fourth Member. The secondary dissolved pore is relatively well developed in the second Member, and the areal porosity can reach 3.19 %. Dissolution mainly affected the unstable component, such as, intragranular dissolution often happened in feldspar, while carbonate cement dissolution is rare. The better the primary residual intergranular pore developed, the better it will be for acidic pore water flow during diagenesis period and the better secondary feldspar and lithic fragment dissolution pores develop.

Discussion

Sedimentary environment

The relatively favorable reservoirs are merely distributed in the sand bodies of distributary channel and river mouth bar which formed in high energy settings. But the sand bodies formed in low energy settings, or with fine grains and thin sand body thickness have already been tight. It reflects that the high-energy sand bodies are conducive to the forming of favorable reservoirs. High-energy sand bodies were deposited in a powerful hydrodynamic force, and have characteristics of large grain, well sorting, well sphericity and psephicity, and high primary porosity and permeability (Fig. 9). So the high-energy sand bodies have stronger ability of resisting compaction, and are favorable for flowing of diagenetic fluid to form secondary pores. Consequently, the existence of high-energy sand bodies is a prerequisite for the forming of favorable reservoirs.

Preservation of porosity

The preservation condition of primary pores in the Xujiahe Formation has certain specific characteristics. Such as, though the burial depth of the second Member is deeper about 1500 m than the fourth Member, there develops more primary pores in the second member than in the fourth member. This phenomenon can be explained as following: (1) lower content of plastic minerals. The plastic minerals (e.g., clay minerals) have lower resistance to resist compaction than rigid minerals (e.g., quartz). Statistical data show that the content of lithic fragment is positive correlation to ACR. It means sandstones in the second member whose lithic fragment content is relatively lower have greater resistance than that of the fourth Member, which is beneficial to the preservation of primary pores. (2) The positive effect of early cementation on pore preservation. The early chlorite film restrained the quartz overgrowth and improved the rock resistance to compaction, which is benefit to the preservation of pores. Carbonate cements (e.g., calcite and ferroan calcite) appeared as blocky precipitate. Though these cements occupied little

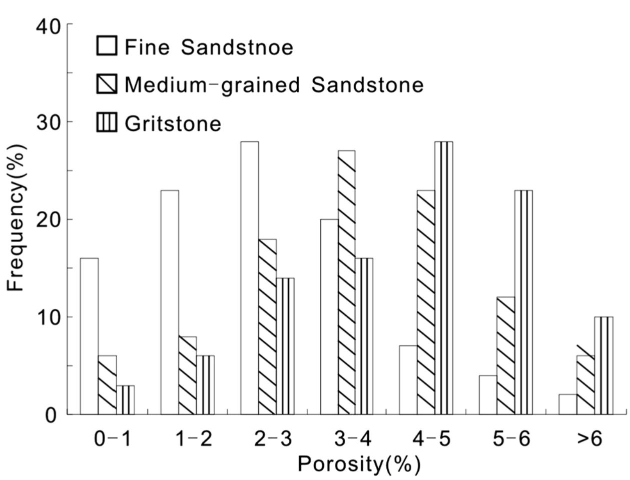

Fig. 9 Distribution of porosity of sandstones with different grain sizes

primary pores, they not only enhanced the rock resistance to compaction but also provided material base for the late dissolution. The late dissolution of carbonate cements released some intergranular pores. (3) Protection of hydrocarbon injection. Because there are abundant source rocks in the Xujiahe Formation, these source rocks experienced multi-episodic hydrocarbon expulsion process in the evolution of Xujiahe Formation. These hydrocarbons not only can be accumulated to form gas pools in appropriate conditions, but also can charge into reservoirs, and thus restrained diagenesis, which can preserve reservoir pores effectively or may form overpressure to protect pores. Sandstones which contain organic matters usually are usually favorable reservoirs. Meanwhile, the content of authigenic quartz is relatively low in the sandstones with abundant organic matters, which demonstrate the protection of hydrocarbon injection.

Tectonism

Under the tectonic compression of Yanshan period and Himalayan period, four sets of fractures are well developed, i.e., N–S, NE–SW, E–W, and NW–SE oriented fractures (Zeng and Li 2010). Based on calculation by the Monte Carlo method and imaging log, the porosity of macro-fractures is generally less than 0.30 % with an average of 0.12 %, and the permeability is chiefly distributed in (5.3–116.5) md. Statistic data of 560 casting thin sections show that the micro-fracture porosity is generally less than 0.55 %, and the average is 0.25 %. The micro-fracture permeability is generally less than 10.0 md, and the average is 4.72 md. The total porosity of micro- and macro-fractures is 0.37 %, accounting for about 10 % of the whole porosity of the reservoirs, which reflect that fractures are effective storage spaces. The permeability of fractures is 2–4 orders of magnitude higher than the matrix permeability, which indicates that fractures are the main seepage channels. The existence of fractures vastly improves the seepage capability on tight gas sandstones. Most of the prolific wells are associated with fractures in the Xujiahe Formation. The distribution of fractures controls the distribution of gas reservoirs and the deliverability of a single well in the tight gas sandstones of Xujiahe Formation.

Overpressure

There is a good relationship between overpressure belt and porosity (Zhu et al. 2009). The reservoir porosity in the overpressure belt is generally greater than that of the same rock types in the normal pressure belt (Fig. 10). The influence of overpressure to the deep buried reservoirs is expressed in the conservation and improvement of porosity

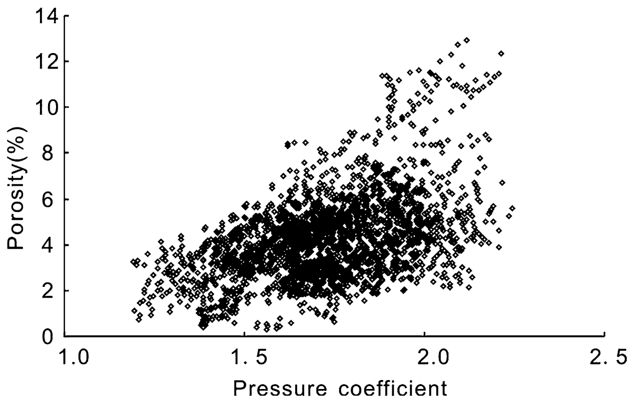

Fig. 10 Relationship between overpressure and porosity

and permeability. On the one hand, overpressure can bear part even the whole lithostatic pressure, which reduce the effective pressure and restrain the compaction to some extent, thus protecting the primary pores effectively. On the other hand, overpressure can promote the formation of micro-fractures, which improved the reservoir permeability and connectivity.

Conclusion

The Upper Triassic Xujiahe Formation in the Western Sichuan Foreland Basin is tight gas sandstones deposited in a terrestrial setting. The sandstones include fine- to medium-grained feldspathic litharenite and lithic sandstone, characterized by low compositional maturity, low cement content, and moderate textural maturity in the aspect of petrology. Secondary pores created by dissolution and micro-fractures are well developed. The porosity is generally less than 6.0 %, and the permeability is less than 0.1 md. Due to the intense diagenesis and tectonism, the tight gas reservoirs are characterized by well-developed natural fractures, great reservoir heterogeneity, complex seepage system, and strong stress sensitivity.

Compaction is the main factor for primary pore space reduction. The cementation of carbonate minerals, quartz, and clay minerals not only reduced the pore space of reservoir but also changed the pore structure, turning the intergranular tubular pore throat into laminar or sutural pore throat, which seriously affect the liquid flow and greatly reduce the reservoir permeability and porosity. Cementation is also a very important factor for the sandstone to be tight. Five controlling factors are responsible for the formation of favorable reservoirs in the Xujiahe Formation, that is, depositional environment with high energy, favorable conserve conditions of pores, dissolution that create secondary pores, tectonism that form natural fractures, and overpressure.

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